UAV Ground Penetrating Radar (GPR): Soil Moisture, Snow, Ground Water Integration

Mahta Moghaddam[1], PI
Sam Prager[1], Asem Melebari[1]
David O'Leary[2], John Fulton[3]

[1]University of Southern California, Los Angeles, CA, USA
[2]USGS, Salt Lake City, UT
[3]USGS, Denver, CO

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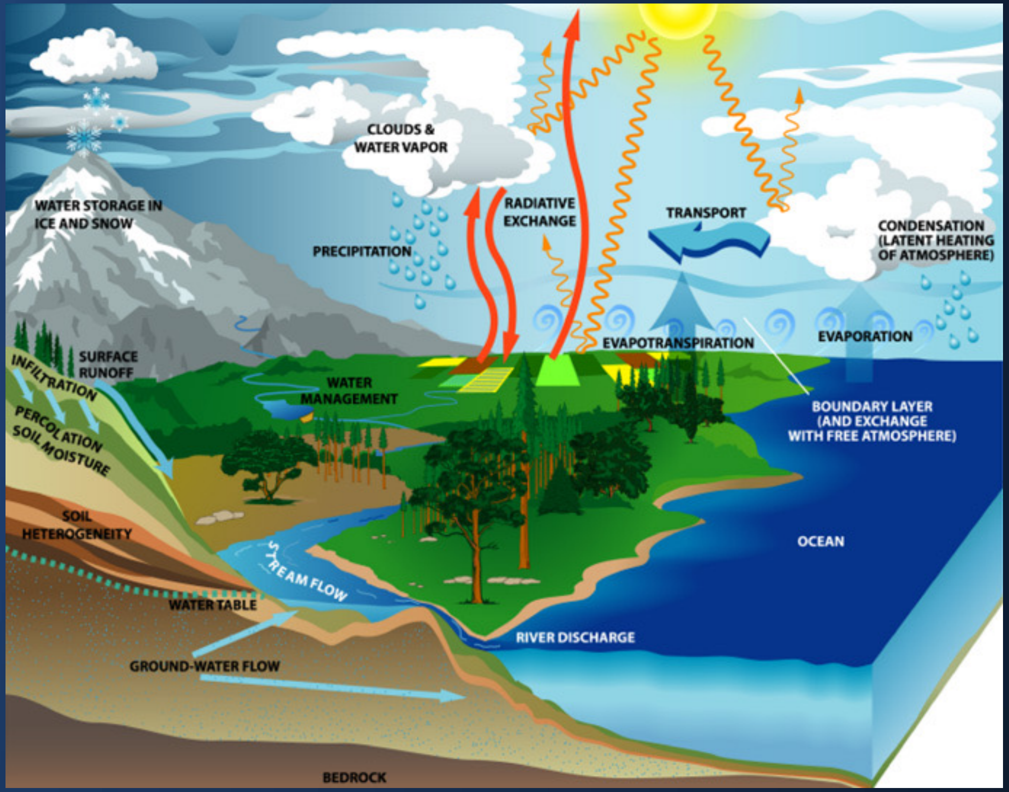
Climate Grand Challenge: Quantification of Water and Energy Cycle

Components of the water and energy cycle that we need to quantify:

- Surface-to-depth profiles of soil moisture
- Groundwater and recharge
- Snow
- Evaporation/transpiration
- Precipitation and clouds
- Ice
- Surface water: river, lake, wetland
- Etc.

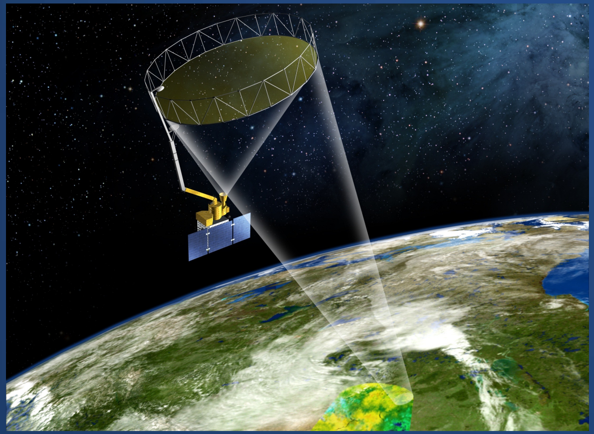
Conceptualization of Global Water Cycle



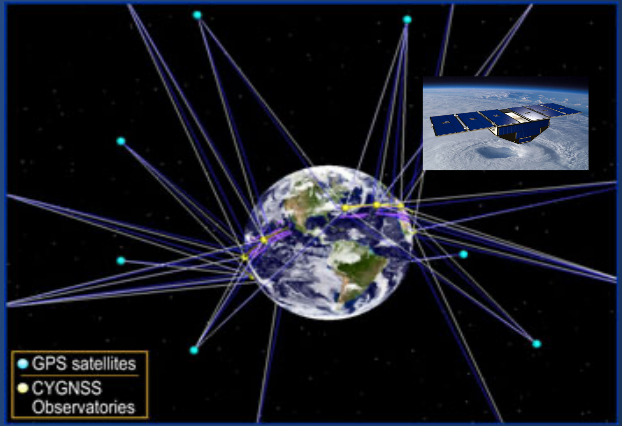
http://www.usgcrp.gov/usgcrp/images/ocp2003/

Envisioned Observation Strategy: in-situ, UAV, airborne, spaceborne, SoOP

Conventional satellite



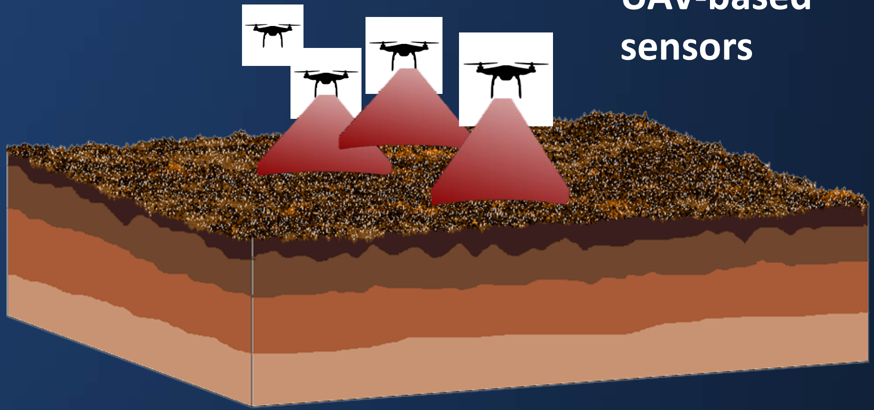
Signals of Opportunity (SoOPs)



Airborne sensors

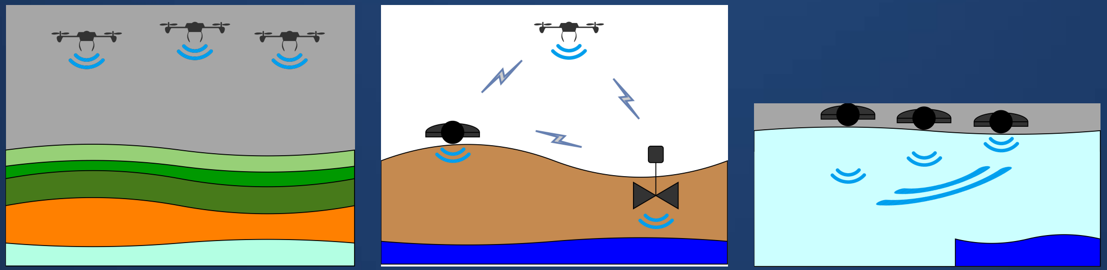
In-Situ sensor networks

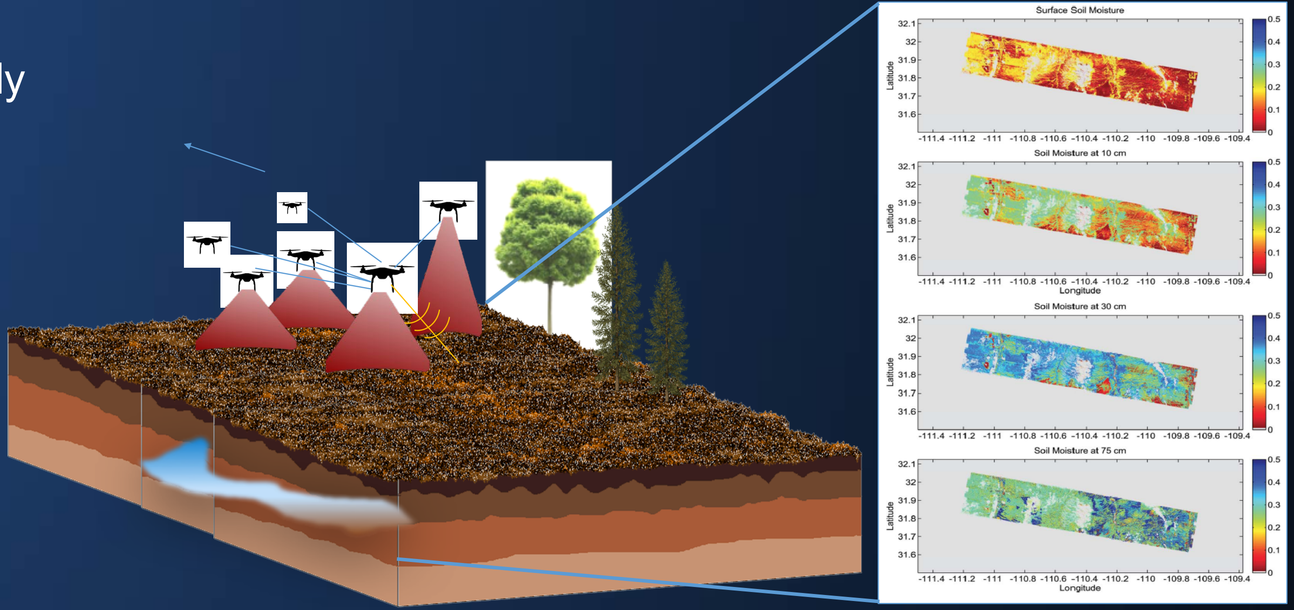
UAV-based sensors



Extensible New System Concept: UAV-based radar Networks and Swarms

- Currently, observation scales between in-situ point scale and high-altitude airborne maps are not addressed
- UAVs can address the gap
- Software defined Radars on UAVs can address the lack of a number of high-resolution observations
    - Groundwater table
    - Soil moisture profiles
    - Snow depth profiles and SWE
    - Software-based radar sensors make it possible for heterogeneous platform networks to work cooperatively



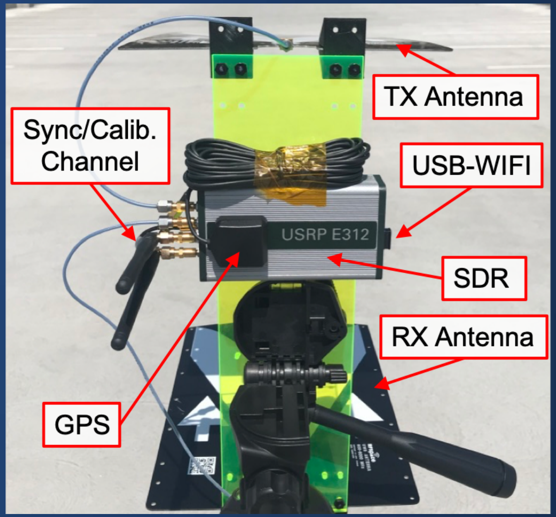


SDR-based Software Defined Radar (SDRadar)

- Small and inexpensive
- Multi-purpose remote sensing devices
- Dynamically configurable in the field:
    - Operating frequency
    - Bandwidth (resolution)
    - Imaging Mode
    - Power
    - SNR

- Developed *frequency stacking* algorithm for synthetic ultra-wideband operation of up to 5 GHz (3 cm resolution!)
- Software basis enables remote updates for improved functionality and expanded operational features

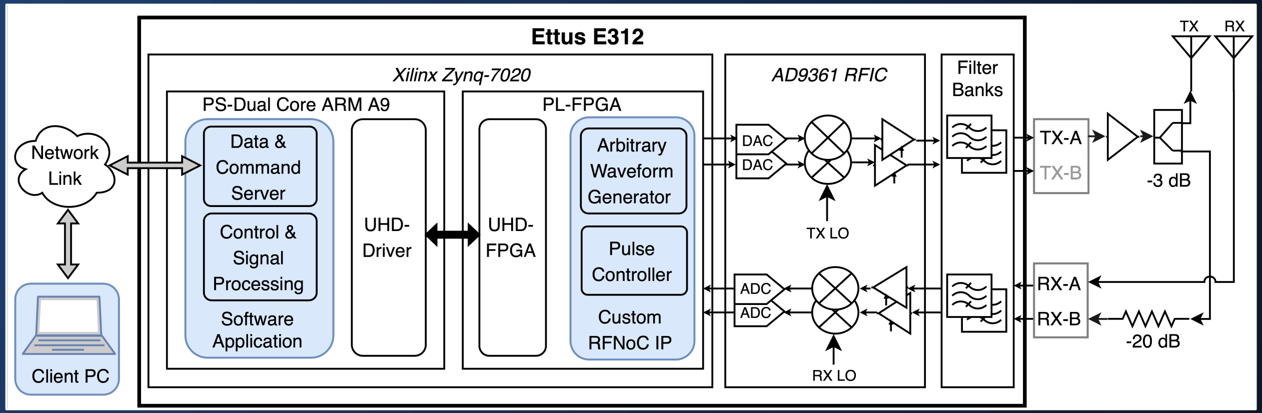
- On-board sensors (GPS, IMU) enhance motion compensation and positional knowledge
- Multi-function waveforms enable simultaneous radar, comms, and synchronization



Ettus E312 USRP: a battery powered 2x2 MIMO SDRadar

Parameter	Value
Sampling Rate, *fs*	50 MHz
Analog Bandwidth, *Bs*	56 MHz
Tunable Center Frequency, *fc*	70 MHz - 6 GHz
TX Gain Range	0-89.5 dB
RX Gain Range	0-76 dB
Size	133 x 68.2 x 31.8 mm
Price	$ 3199.00

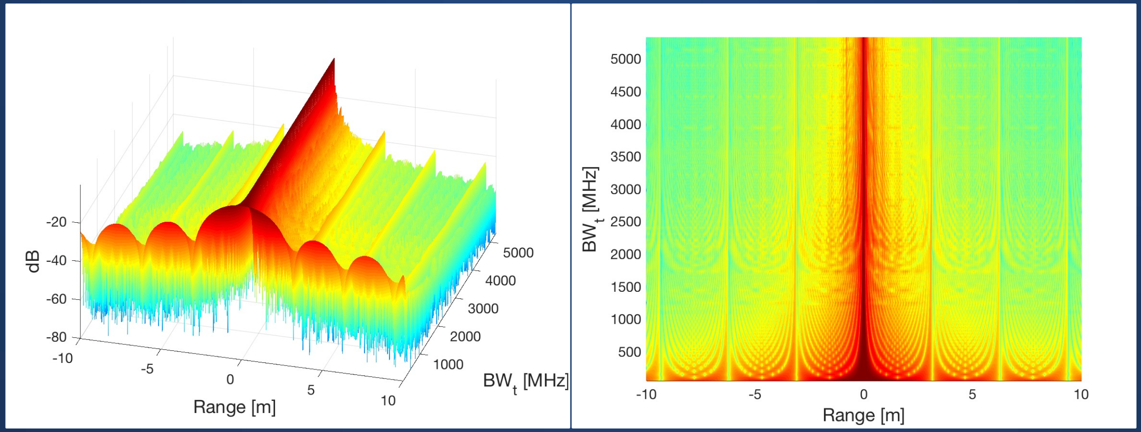
USRP E312 SDR Specifications



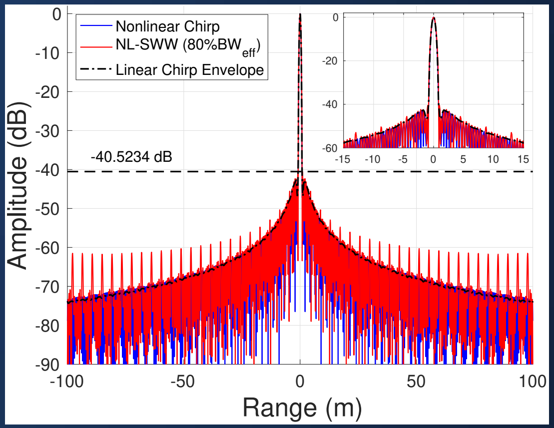
SDRadar software and firmware implementation

Synthetic Wideband Waveform (SWW) SDRadar

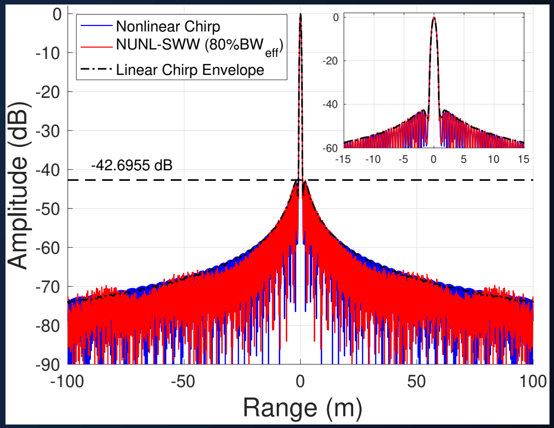
- Chief limitation of SDR is low instantaneous bandwidth, which results in poor resolution
- SDRs, however, have a wide tunable frequency range (10 MHz – 6 GHz).
- We coherently synthesize an ultra-wideband waveform using *frequency stacking* algorithm* to achieve high range resolution
- Improved *non-uniform frequency stitching* (NUFS) algorithm, grating lobe suppression (GLS) filter and non-uniform frequency step size used to mitigate SWW processing artifacts (grating lobes)



Compressed SWW pulse as total bandwidth increases. Main lobe width indicates resolution performance.



FS Algorithm. Note presence of contaminating grating lobes



Improved NUFS Algorithm.

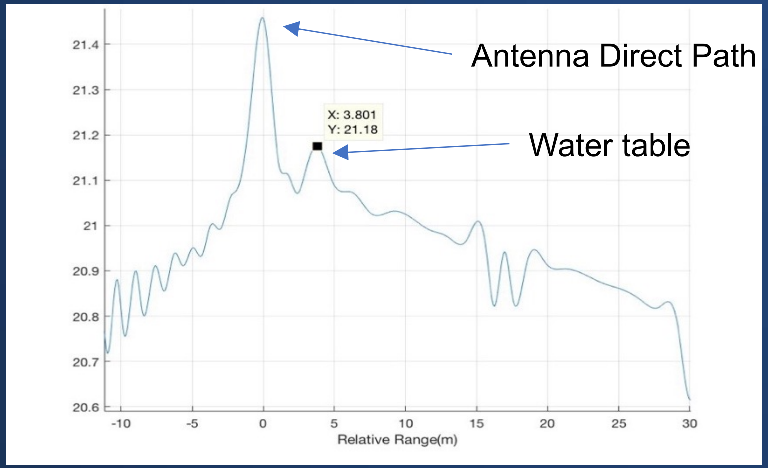
* Prager, S., Thrivikraman, T., Haynes, M., Stang, J., Hawkins, D. and Moghaddam, M. “Ultra-Wideband Synthesis for High-Range Resolution Software Defined Radar,” in IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 6, pp. 3789-3803, June 2020.
** Prager, S., Hawkins, D. and Moghaddam, M. “Arbitrary Nonlinear FM Waveform Construction and Ultra-Wideband Synthesis.” in IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2020. Waikoloa, HI.

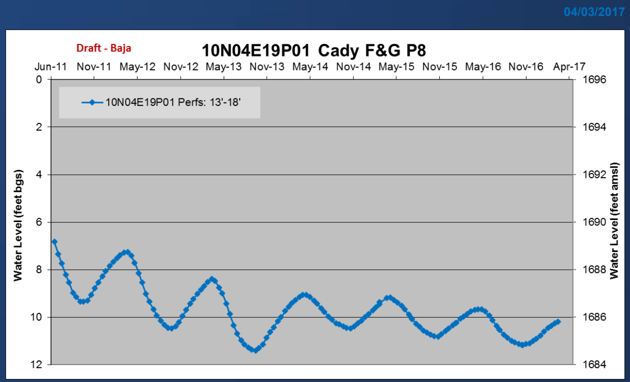
SDRadar Application Example: Water table sounding

- Testing Site: **Camp Cady Wildlife Area (Site P8)**
- Desert riparian habitat along the (primarily subterranean) Mojave River

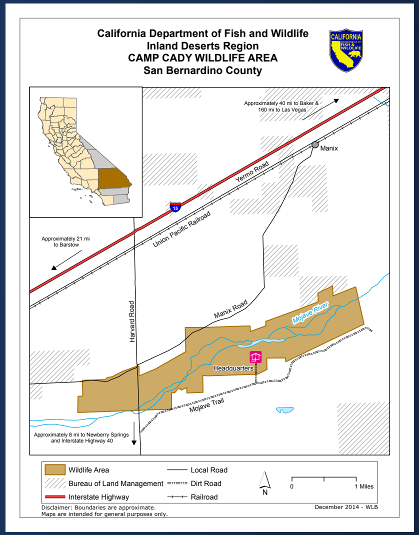
<u>True Water Table Depth:</u> **~12 ft.**

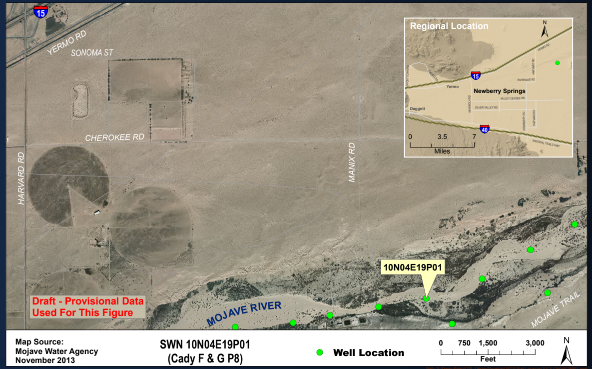
<u>Water Table Depth Estimation:</u>
Assuming a Relative Permittivity 2: **~14.8 ft**
Assuming a Relative Permittivity 3: **~12.4 ft**





SDRadar water table sounding results (Left). Water level as measured at Site P8 well (Right)





Camp Cady Wildlife Area Location

Images from SDRadar sounder test

- Plot Marker represents range to water-table peak detection relative to antenna separation range in meters
- **Note:** The permittivity (soil dielectric) generally increases as soil becomes more clay-like.

Water Table Model: understanding the signal

Water Table model (Van Genuchten)[1]

$$\theta(z) = \begin{cases} \theta_R + (\theta_S - \theta_R)\left(1 + \left|{}^{h}/_{h_0}\right|^n\right)^{{}^{1}/_{n}-1} & z < z_{table} \\ \theta_S & z \geq z_{table} \end{cases}$$

$$h = z - z_{table}$$

Water table (WT) model parameters: h_0,n, and z_{table}

z_{table}: depth of the water table

z depth index

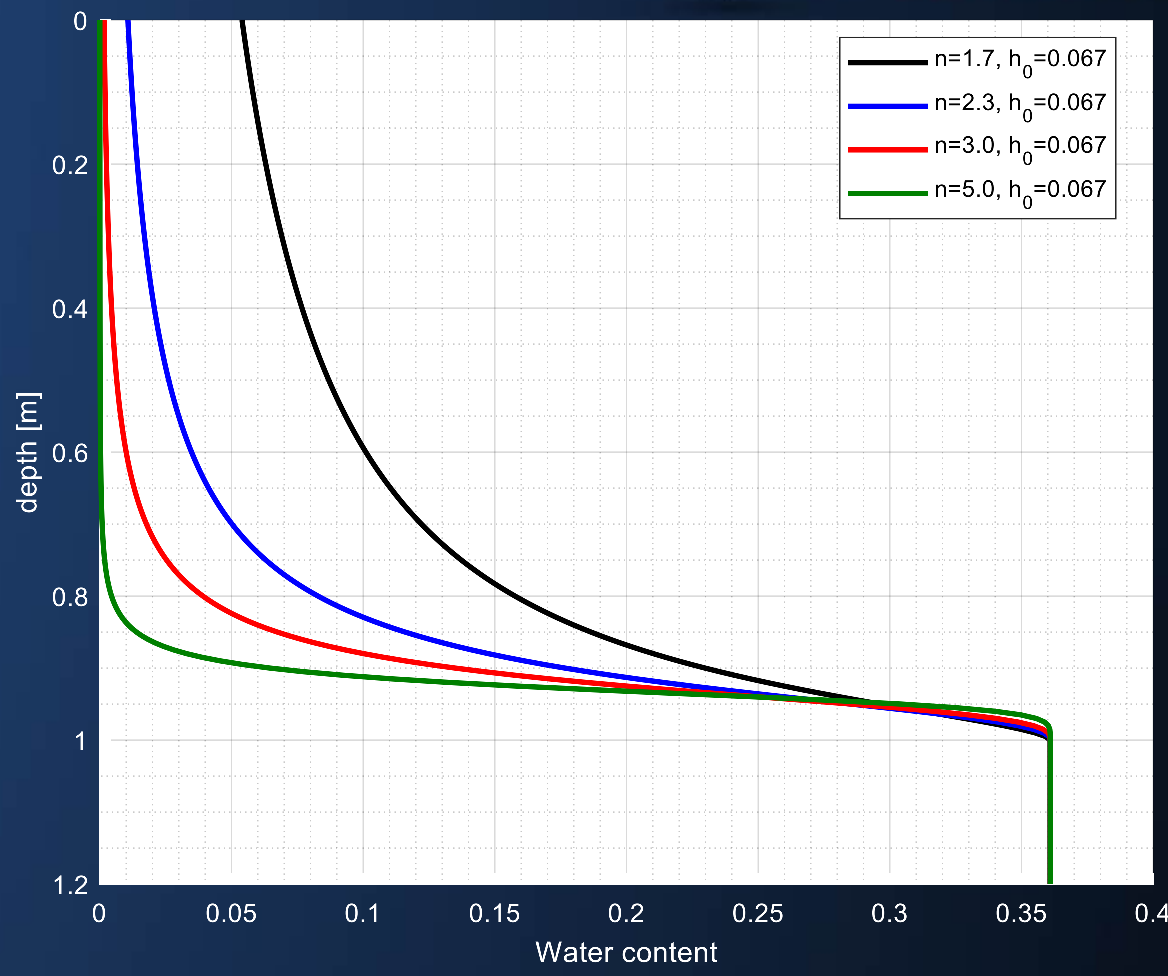
θ_R residual water content

θ_S water content at saturation

h_0 air-entry point (scaling parameter)

n pore distribution index

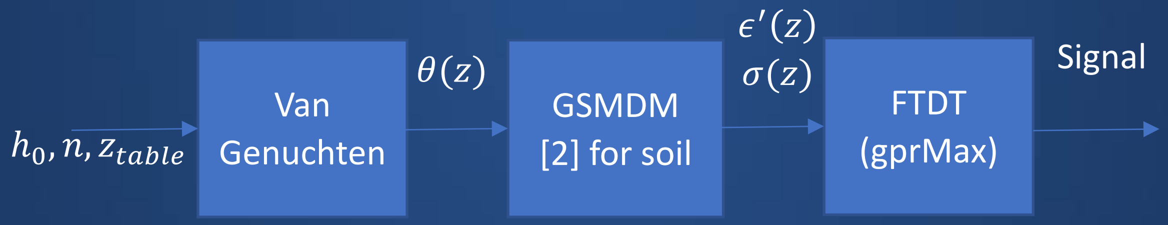
h capillary pressure head

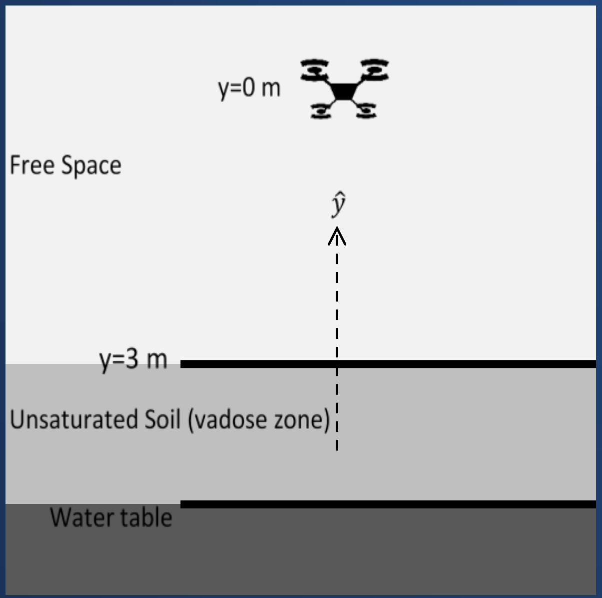


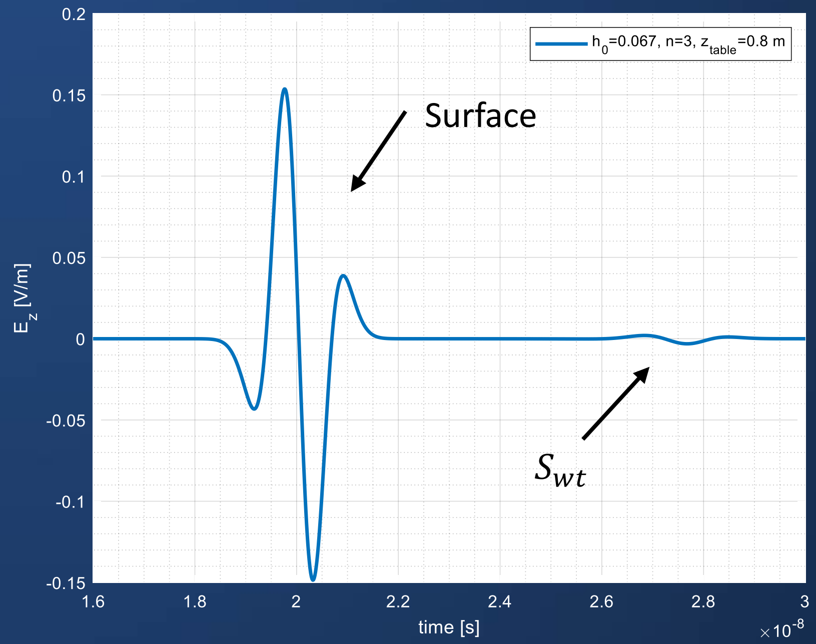
[1] Costabel, S., Günther, T., 2014. Noninvasive estimation of water retention parameters by observing the capillary fringe with magnetic resonance sounding. Vadose Zone J. 13 (6).

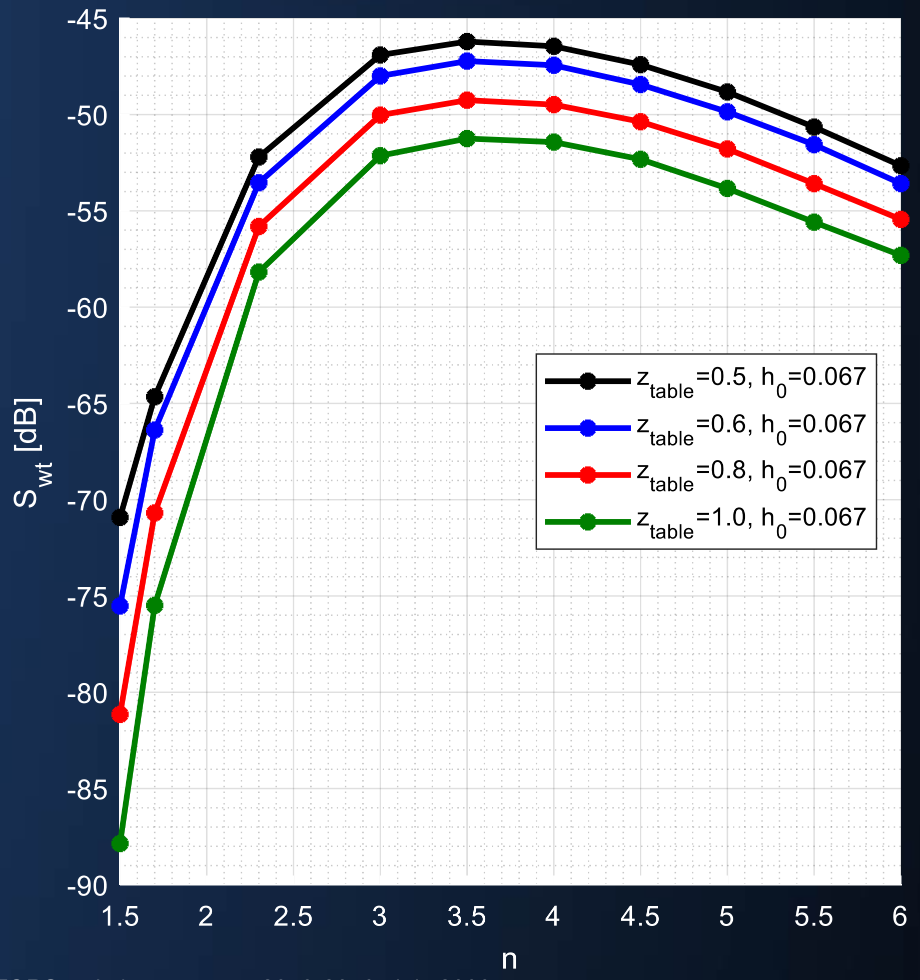
Radar EM Simulation Setup (1)

Water table simulation setup:



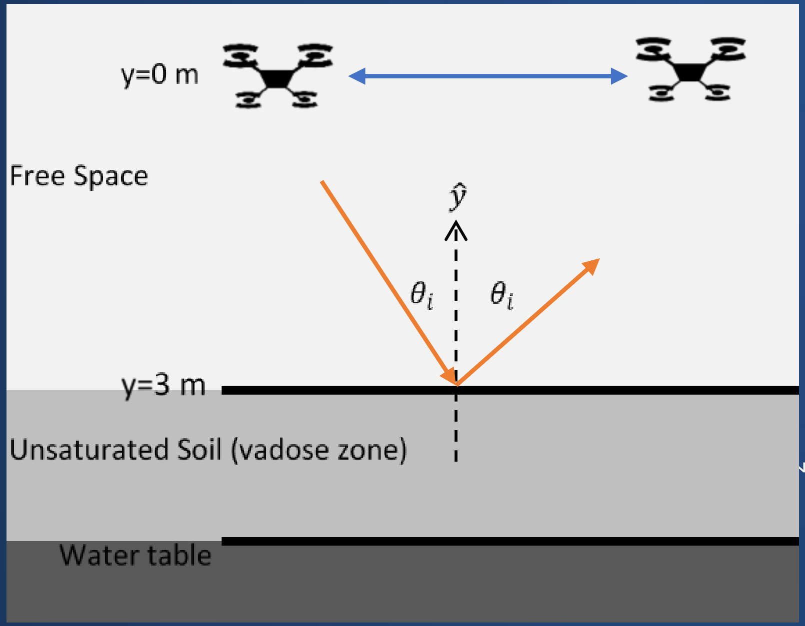


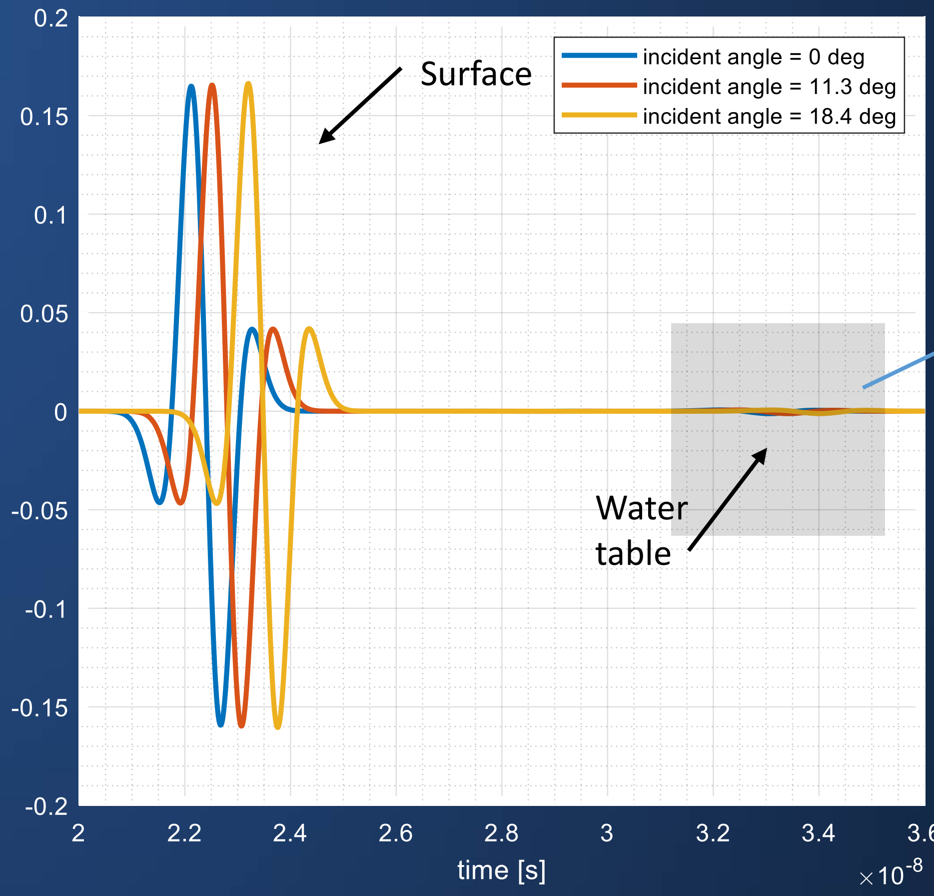


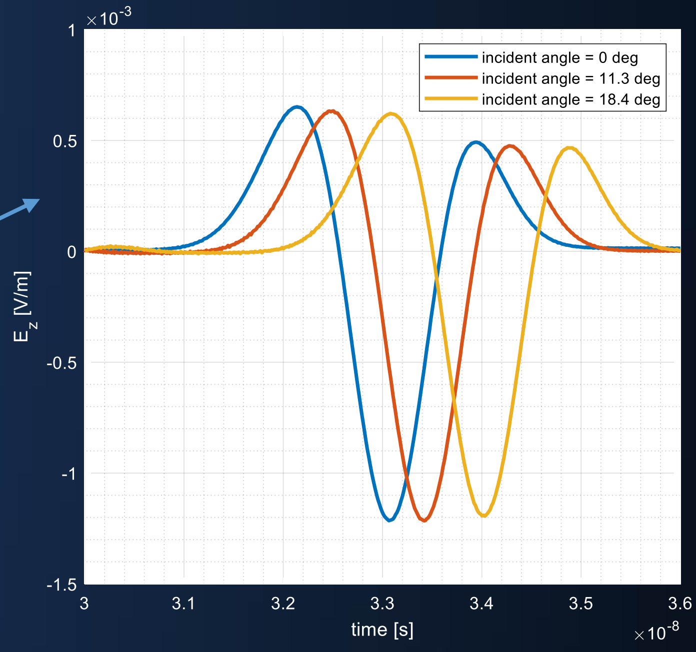


[2] V. L. Mironov, L. G. Kosolapova and S. V. Fomin, "Physically and Mineralogically Based Spectroscopic Dielectric Model for Moist Soils," in *IEEE TGRS*, vol. 47, no. 7, pp. 2059-2070, July 2009.

Radar EM Simulation Setup (2)



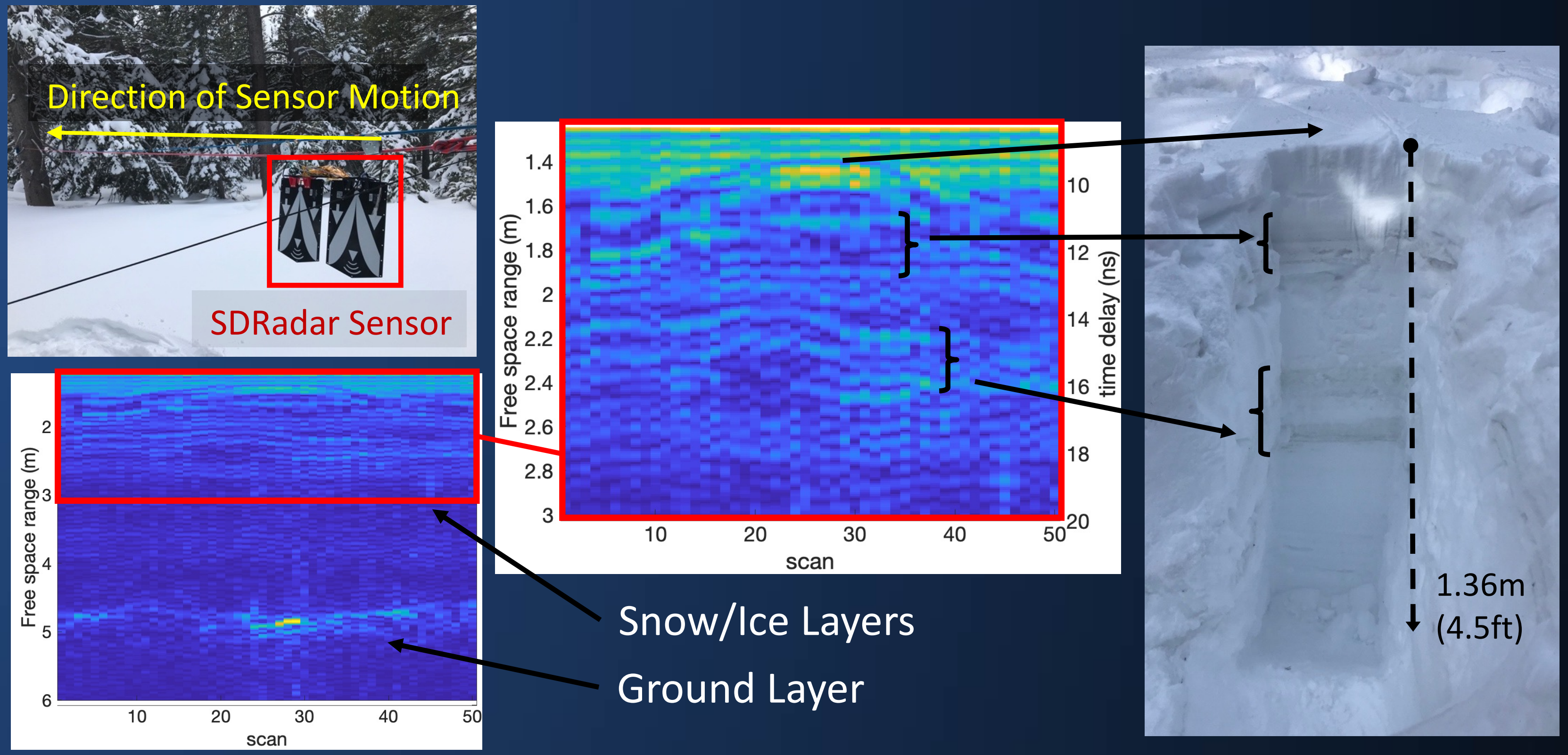




- SDRadar observations show similar behavior to the simulations
- We will use this simulation setup in a retrieval mode to estimate soil profile and water table parameters

SDRadar Application Example: Snow/Ice Penetrating Radar

- Near Mammoth Lakes, CA
- SDRadar sensor moved across 25m section of a snow bank
- 2.5 GHz synthesized BW (600-3100 MHz)
- Snow depth: ~7-8 ft.
- Snow depth and stratigraphy imaged by SDRadar

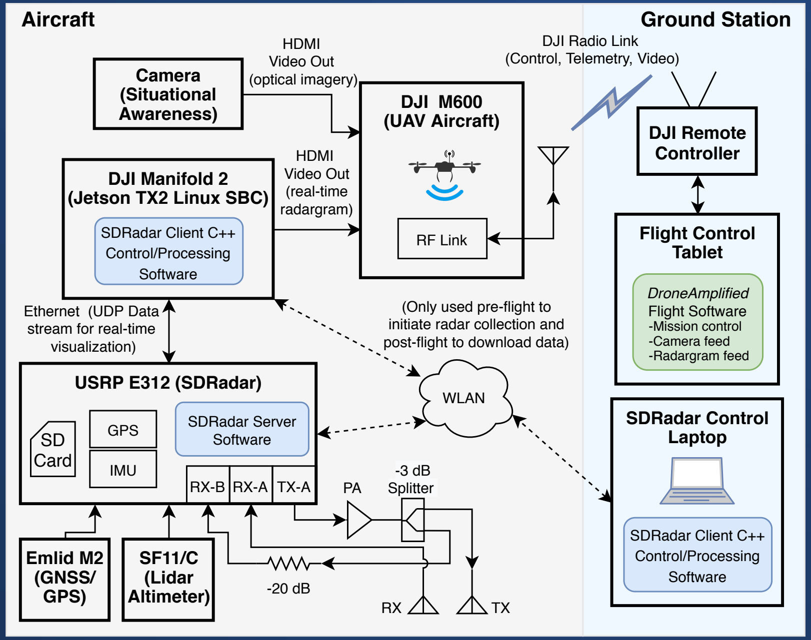


Snow penetrating SDRadar imaging

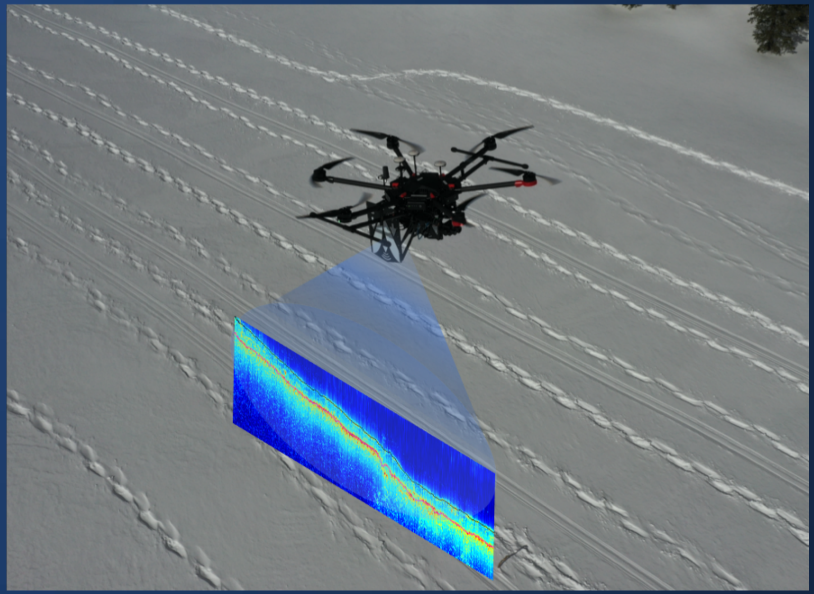
Snow pit cross-section

Integration of UAV-SDRadar Payload

- DJI M600 aircraft
- Battery-powered SDRadar sensor with integrated IMU+GPS
- Laser altimeter and external RTK GPS/GNSS RTK used for cm-level position determination
- Motion compensation applied for tomographic and SAR processing
- Plan to ultimately use Nvidia Jetson TX2 GPU processor onboard for fast SWW image reconstruction and real-time radargram visualization
- Range resolutions of up to 10 cm (1.5 GHz bandwidth) demonstrated experimentally in flight



UAV-SDRadar payload system diagram



UAV-SDRadar in flight over snow field

UAV-SDRadar integrated payload

Prager, S., Sexstone, G., McGrath, D., Fulton, J., and Moghaddam, M. ”Snow Depth Retrieval with an Autonomous UAV-mounted Software Dened Radar,” submitted to IEEE Transactions on Geoscience and Remote Sensing.

UASnow 2020 Field Campaign: Cameron Pass, CO

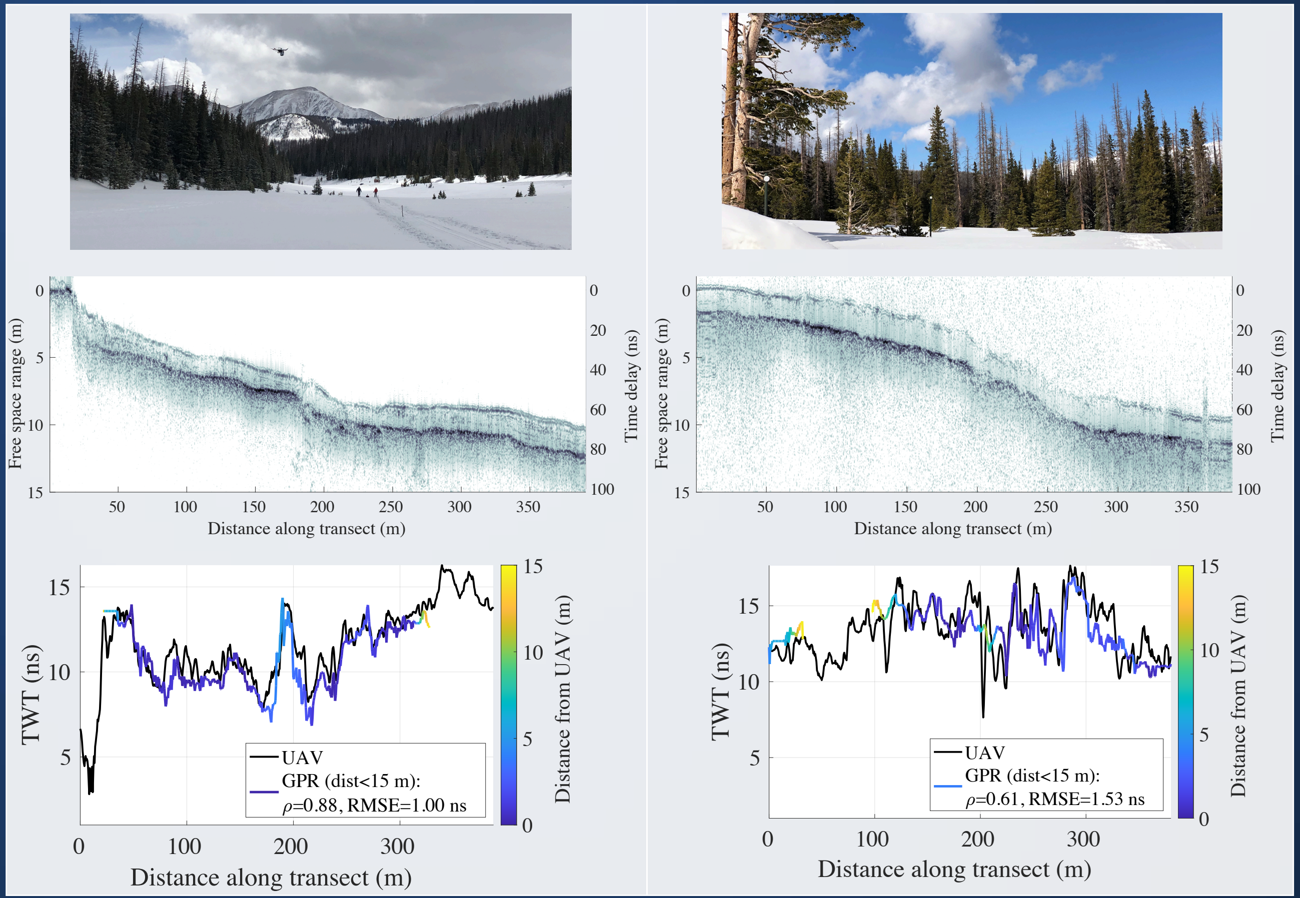
- March 2020 field campaign to image snow fields in Cameron Pass, Colorado using SDRadar
- SDRadar snow depth two way travel time (TWT) compared with ground based sled-GPR measurements
- Two transects flown

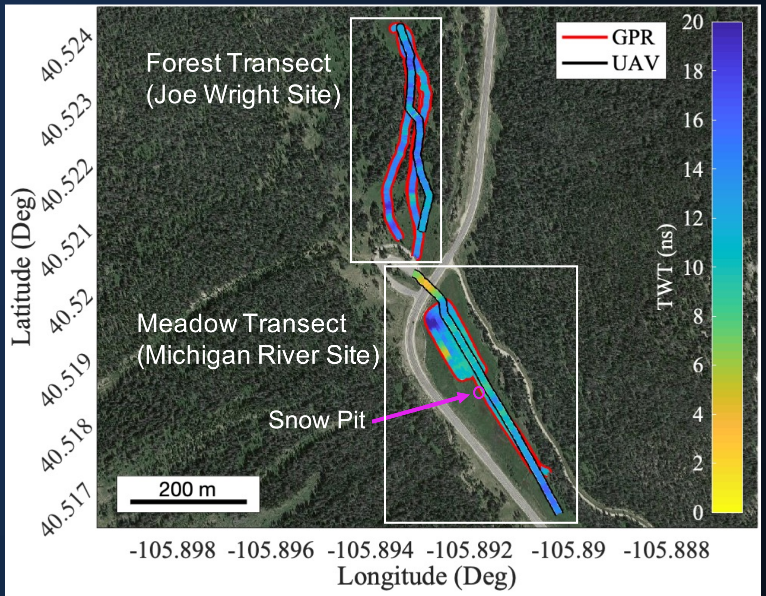
Meadow transect | Forest transect

Transects

Motion-Compensated Radargrams

Measured snow-depth (two way travel time (TWT))





UASnow 2020 test sites

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- SDRadar snow depth two way travel time (TWT) compared with ground based sled-GPR measurements
- Two transects flown

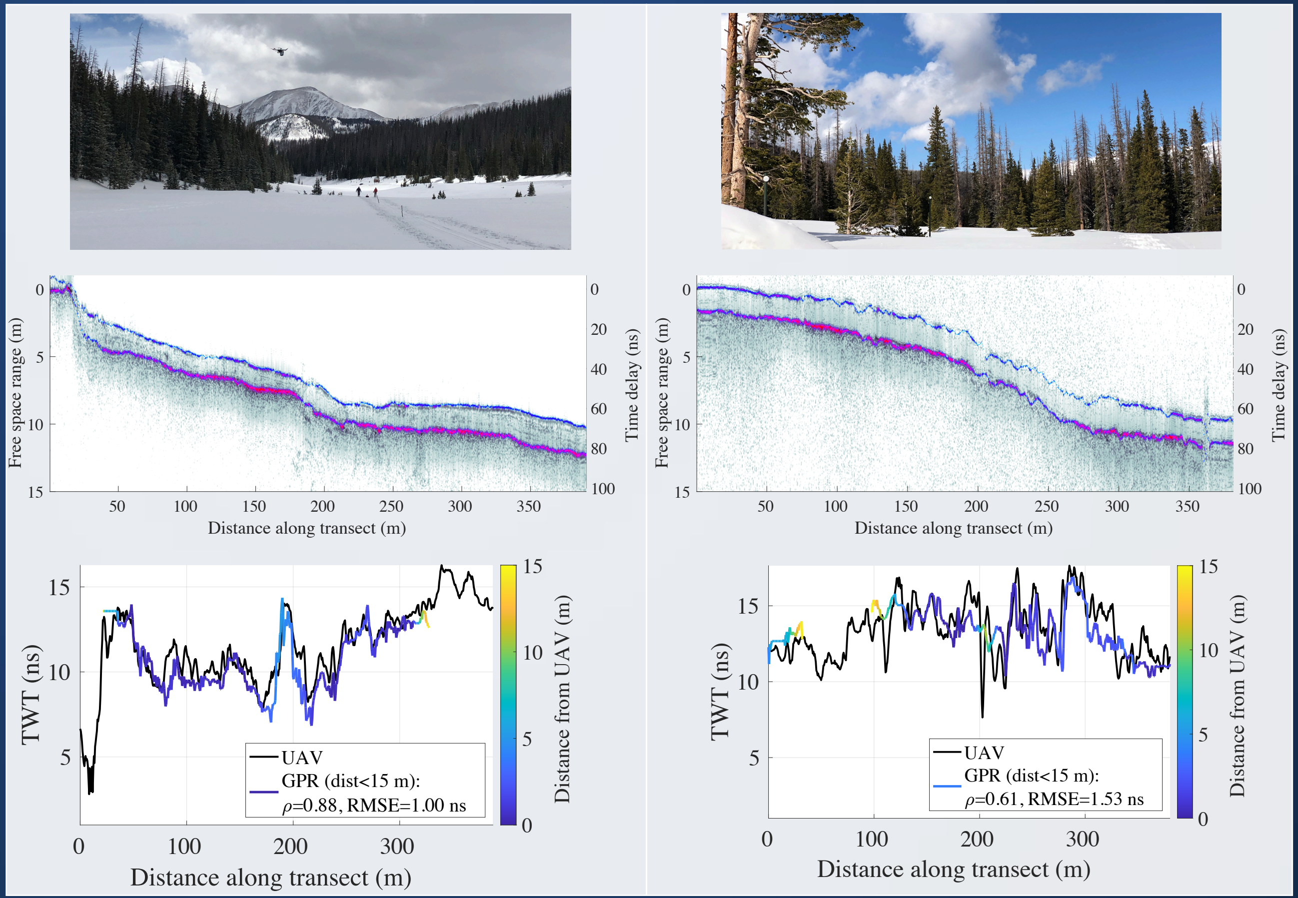
Meadow transect

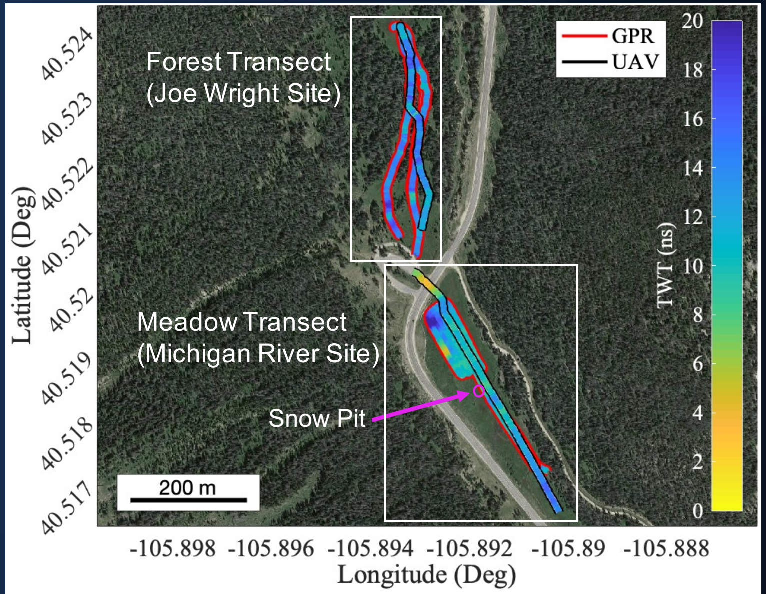
Forest transect

Transects

Detected snow/ground interface reflections

Measured snow-depth (two way travel time (TWT))

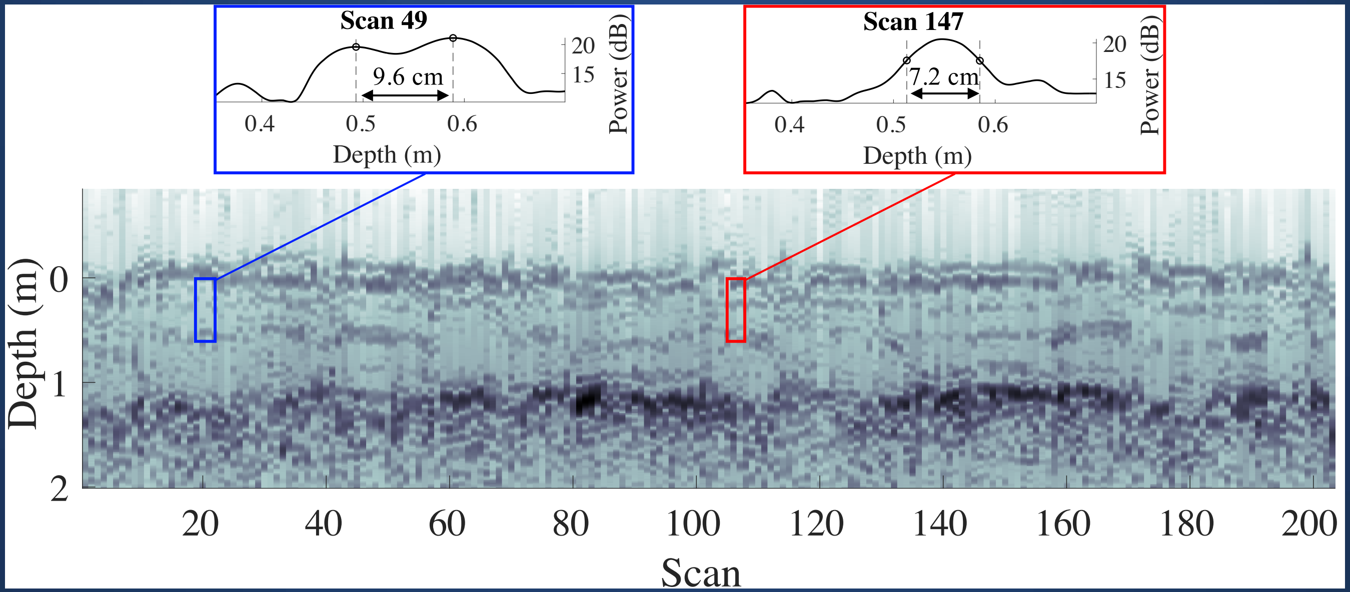




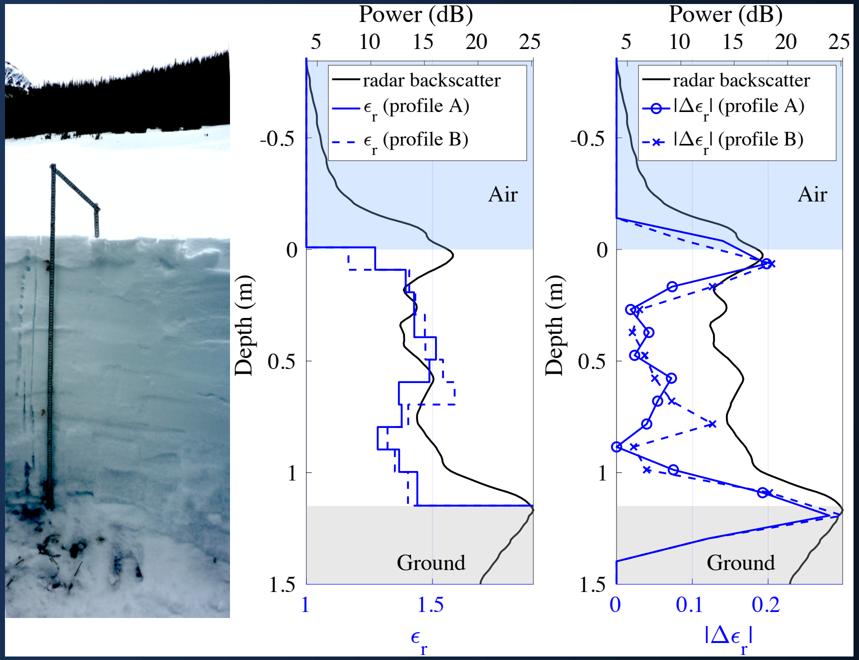
UASnow 2020 test sites

UASnow 2020 Field Campaign: Cameron Pass, CO

- UAV hovered over snow pit along Meadow Transect
  - Snow depth: 1.21 m
  - Avg snow dielectric: 1.41
- Average radar backscatter profile compared with measured snow dielectric



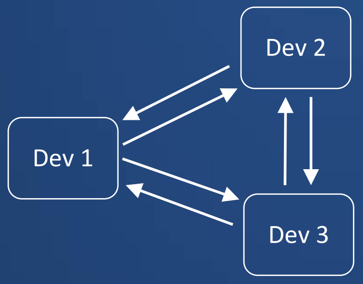
Radargram showing snow stratigraphy measured at snow pit



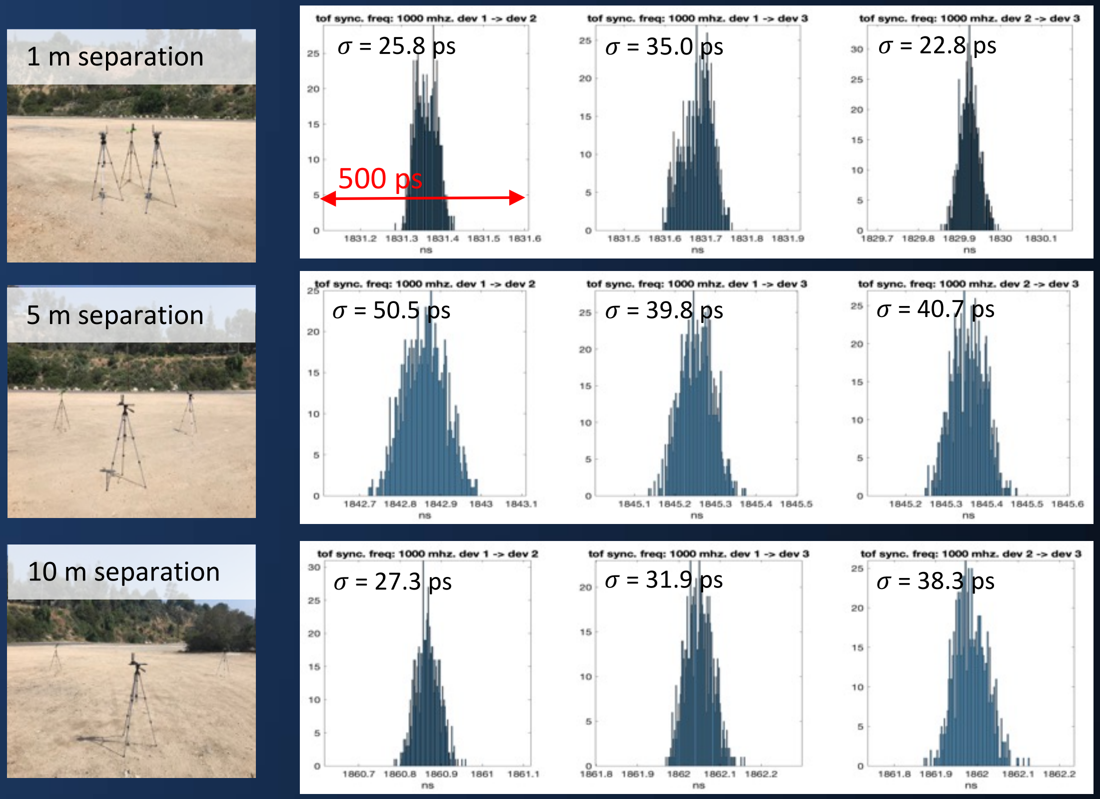
Snow pit (left), radar backscatter compared with measured snow pit dielectric profile (center) and measured snow pit dielectric gradient (right).

Sub-nanosecond Wireless Synchronization

- Developed sub-nanosecond coherent synchronization method for SDRadar
  - This is a major development that will enable coherent MIMO processing and tomographic mapping of the subsurface



- 3 Sensors arranged in static triangular formation
- RF synchronization routine performed once per second
- 1000 measurements taken (~17 minutes)
- After synchronization, each node knows node-to-node distances for entire network
- Single measurement Time of Flight (TOF) precisions < 100 ps (3 cm) with 96% confidence

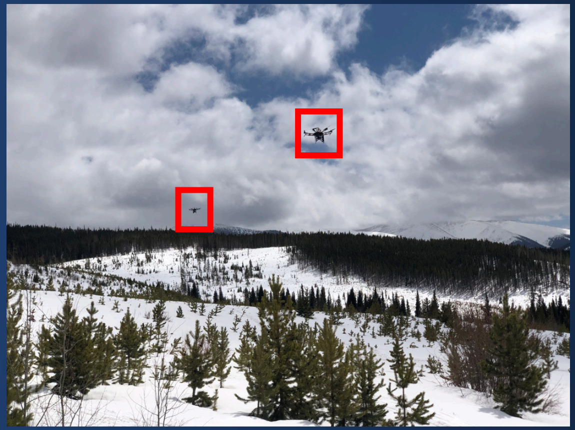


3-sensor wireless synchronization experiment

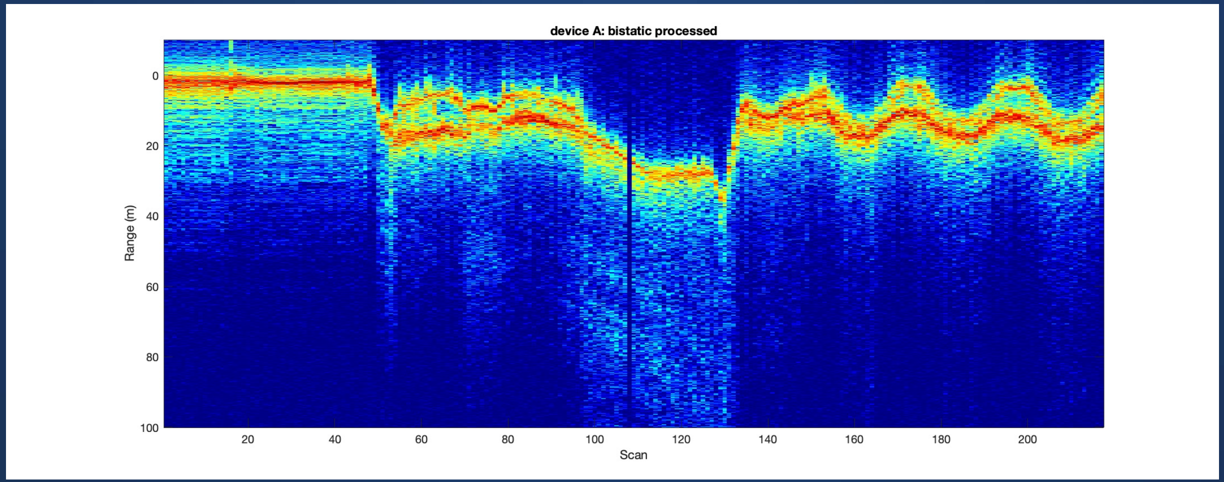
Prager, S., Haynes, M. and Moghaddam, M. "Wireless Subnanosecond RF Synchronization for Distributed Ultrawideband Software-Defined Radar Networks," in IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 11, pp. 4787-4804, Nov. 2020.

UASnow 2021 Bistatic UAV-SDRadar Test Flights

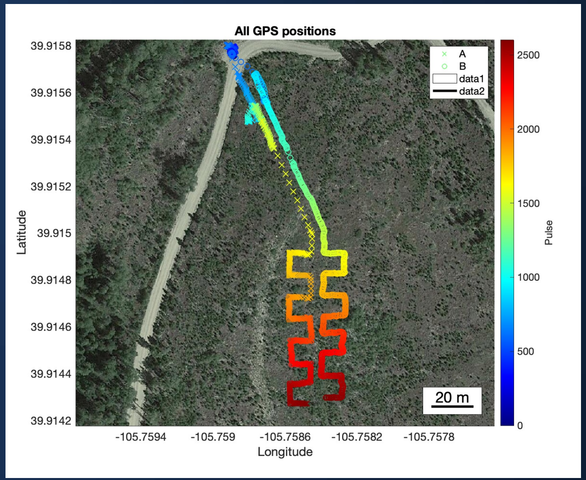
- Initial test flight with two UAV-SDRadar systems operating bistatically
- Stepped frequency bistatic SWW synthesized with wireless synchronization performed at each frequency step for coherent operation



Two bistatic UAV-SDRadar systems in flight



Initial bistatic UAV-SDRadar radargram



GPS Coordinates of two UAV-SDRadar systems

Next Steps

- More tests to image soil moisture profiles, groundwater, and snow sites with UAV
- Bistatic, Multistatic, and MIMO coherent UAV Swarm tests
- Design lower frequency antennas for bathymetry and deep sounding from UAV-based SDRadar
- Expand role of embedded Jetson TX-2 GPU-based processor
- Further develop electromagnetic processing algorithms for dielectric profile inversion
- Advance multi-UAV path planning and flight control schemes (AIST SPCTOR project; NOS)
- Joint operation of UAV-SDRadar with ground-based in-situ sensor networks (AIST SoilSCAPE & SPCTOR projects; link to NOS)